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Dual-Band Dual-Polarized Waveguide Slot Antenna for SAR Applications

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***Abstract*—The design of a shared-aperture waveguide slot antenna operating in dual-band and dual-polarization (DBDP) is proposed in this paper for synthesis aperture radar (SAR) applications. The frequencies of the antenna are in both L- and C-band with frequency ratio of 4:1. The C-band horizontal-polarized subarray antenna is achieved by 16 V-shaped slots opened on a ridged waveguide, while the vertical-polarized subarray is realized by 16 longitudinal slots displaced from the centerline on the other ridged waveguide. The L-band vertical-polarized subarray is comprised by four groups of longitudinal slots cut in the metal-wall interlacing with the C-band dual-polarized antenna array sharing the same aperture. The L-band waveguide is a multi-ridge cavity under the C-band waveguide. A DBDP antenna module comprising 4×16 C-band dual-polarized elements and 1×4 L-band elements was manufactured in aluminum alloy. Experimental results show that the proposed antenna can obtain excellent electromagnetic performance and maintain satisfactory thermal and mechanical properties for space-borne SAR applications.**

***Index Terms*—Dual-band, dual-polarization, waveguide slot antenna, synthetic aperture radar (SAR).**

I. Introduction

ANTENNAS equipped with properties of multifunctionality and compact-size are always desired in practical electronic applications. In particular, antenna arrays operating in multiple frequency bands with shared-aperture have great advantage in modern wireless communication and radar systems, such as synthetic aperture radar (SAR) [1]. For an advanced SAR system, dual- or multiband operation can provide abundant resolution, penetration and reflection characteristics from covered targets, and dual-polarization can provide polarization information from observed targets. Currently, the multi-band and multi-polarized antennas attract great interest in SAR application. Printed patch antenna is a good candidate to design multi-band shared-aperture antenna based on the slot-loaded technique [2]-[8]. A typical design is a tri-band dual-polarized shared-aperture microstrip antenna array operating at L-, S- and X-bands [9]. Though the microstrip antennas realized by printed circuit board (PCB) technique on substrate have great superiority for accommodating multiple antennas into a shared-aperture, problems still exist in terms of losses at high-frequency, mutual coupling interference between bands and fabrication difficulty regarding to multi-layer PCB.

On the other hand, for advanced wireless applications like space-borne radar, it is essential that the antenna array possesses high radiation efficiency and meanwhile is able to withstand harsh temperature conditions and cosmic radiation [10]. The above-mentioned PCB-based microstrip antennas are, obviously, hard to adapt to these conditions. In addition, for the special application of limited angle scanning, a subarray configuration formed by certain number of antenna elements and a power-divider network is always wanted. Such subarray would be terminated with active modules, i.e., transmit/receive (T/R) modules, at the radio-frequency (RF) back-end. To further achieve beamforming capability and agility, an active phased array should include subarrays, T/R modules, real-time delays, antenna control electronics and power supply [11]. Generally, waveguide-based slot antennas are invariably preferred to satisfy SAR requirements due to their superior performance such as low-loss, great robustness and nearly perfect heat-conducting property. However, unlike the two-dimensional microstrip antennas, it is undoubtedly that constructing multiple waveguide antennas in the same aperture is difficult on account of the bulky three-dimensional structure of the waveguide. To date, the majority of research works focus on dual-polarized antennas sharing one aperture, the most common designs of which are the dual-polarized slotted waveguide antenna arrays operating in the same frequency band [12]-[15]. To simultaneously achieve more operating frequency bands, a dual-frequency dual-polarized antenna array was reported with horizontal polarized (HP) antenna working at 35 GHz band while vertical polarized (VP) antenna working at 30 GHz [16]. Furthermore, a design of an L-band dual-polarized and X-band single-polarized shared-aperture array is reported in [17], the X-band antenna array of which has relatively lower aperture efficiency of 66.9% because of the larger spacing of the radiation elements for providing sufficient space to design the L-band elements.

In this letter, a highly-integrated shared-aperture waveguide slot antenna module operating in dual-band dual-polarization (DBDP) is investigated. The antenna module comprises 4×16

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C-band dual-polarized elements and 1×4 L-band vertical-polarized elements. Two designs of antenna operating in C- and L-band respectively are interlaced with each other to achieve a low-profile and compact size while the dual-band radiation performance can be well maintained independently.

II. Structure of The Proposed Antenna

The detailed structural configuration of the proposed waveguide slot antenna module is shown in Fig. 1. The complete antenna module can be considered as formed by two C-band slotted waveguide antenna arrays operating in different polarizations, namely, vertical-polarization (V-Pol.) and horizontal-polarization (H-Pol.), and one L-band linear slotted waveguide antenna. The C-band dual-polarized antenna is developed from an X-band dual-polarized waveguide slot filtering antenna array featuring in low cross-polarization and high-efficiency [14]. Particularly, the C-band V-Pol. antenna designed in this work consists of four linear subarrays in the y-direction, which is realized by a ridged waveguide with 16 offset longitudinal slots, while the C-band H-Pol. antenna is composed of four linear subarrays constructed by another ridged waveguide with 16 V-shaped slots. Both of the C-band H-Pol. and V-Pol. subarrays are excited by eight probes from the bottom, which are marked with "C-band H-pol. feeding probes" and "C-band V-Pol. feeding probes" in Fig. 1(b). The C-band H-Pol. subarrays are interlaced with the V-Pol. subarrays but having around $\lambda/4$ overtop the V-Pol. subarrays, where λ is the free-space wavelength of the center frequency at the desired C-band. On the other hand, the L-band subarray is formed by four groups of radiating slots to achieve vertical polarization, as shown in Fig. 1(c), the subarray of which is also interlaced with the C-band subarrays. Such design configuration possesses advantages for accommodating L- and C-bands antenna into a shared-aperture with less signal cross-talk and high structural integration, as well as the flexibility to achieve a 4:1 frequency ratio, i.e., the ratio of the center frequency in C-band to that in L-band.

It should be noted that the spacing between the subarrays is restricted by the maximal beam scanning angle of the array. In order to obtain a compact size, the corresponding widths (compared with the desired operating wavelength) of the C-band H-Pol. and V-Pol. waveguide channels for power transmission, i.e., the rectangles marked with purple- and green-color lines respectively as shown in Fig. 1(b), are further reduced compared with those of [14]. Furthermore, there is a metallic cavity placed under the C-band antenna to serve as the L-band waveguide channel, as depicted in the polygon marked with red-color dashed line in Fig. 1(b). The width of the L-band waveguide channel equals to the accumulation of that of three H-pol. and four V-pol. C-band waveguide channels, while the length is the same as the C-band waveguide channels' along the y-direction. The space below the waveguide ① is reserved for the mechanical installation of RF back-end modules. In order to adjust the waveguide working wavelength for a desired spacing between adjacent radiating slots, two extra metal ridges are protruded from the bottom of the L-band waveguide channel, as

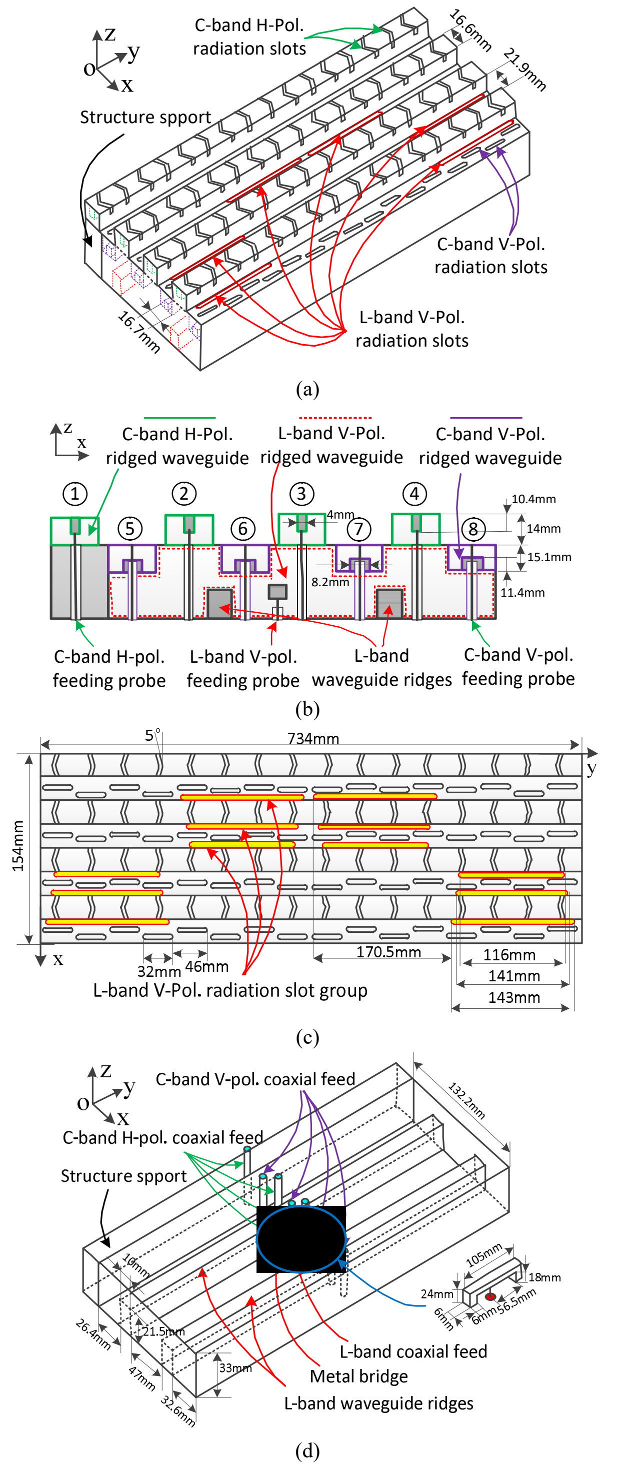

Fig. 1. Detailed configuration of the proposed DBDP antenna module. (a) Three-dimensional (3-D) view of the complete module. (b) Top view of the module. (c) Cross section of the module. (d) L-band waveguide cavity without top C-band waveguides.

shown in Fig. 1(d). Therefore, including the two ridges made up of the two C-band V-Pol. waveguide channels at the upper waveguide wall, the L-band waveguide channel possesses totally four metal ridges to miniaturize the volume and improve impedance matching of the waveguide. Eight feeding probes are constructed by coaxial lines to excite the dual-polarized C-band subarrays. The feeding coaxial lines for waveguides ② ③ ④ ⑤ ⑥ ⑦ ⑧ of the C-band subarrays are inserted through

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the bottom L-band ridged waveguide, as shown in Fig. 1(b) and (d). A metal bridge with a vertical probe is utilized for the excitation of the L-band waveguide slot antenna, as shown in Fig. 1(d). Furthermore, as there is limited space for designing the L-band slots on the aperture of the highly-integrated C-band antenna array, each L-band radiating slot consists of three adjacent slots with different lengths to achieve a good impedance matching, as shown in Fig. 1 (c).

III. Design and Analysis of The Proposed antenna

To realize the DBDP shared-aperture antenna with desired performance, the proposed antenna module is systematically analyzed using the commercial electromagnetic simulation tool HFSS®. The spacing between subarrays and the length of the subarrays are firstly determined according to the required scanning angle. Assuming the maximal beam scanning angle in *xz*-plane is equal to 20° while it is not necessary for beam scanning in *yz*-direction, the estimated spacing along the *x*-direction (d_x) is about $0.7\lambda_h$, where λ_h is the operating wavelength of the high frequency in the desired C-band. Meanwhile, as the subarrays are waveguide resonant slotted arrays, it is known that the length of the subarrays is restricted by the operating bandwidth. Though a wider bandwidth can be achieved by adopting an array separated into subarrays and fed by a waveguide divider [15], such implementation would increase the array's profile and structural complexity. Furthermore, the two-dimensional size and the radiation power of an array are normally pre-determined for a SAR system deriving from the required azimuth resolution, observation swath, ambiguity and sensitivity [18]. Therefore, a longer/larger subarray means that the number of the subarray in the complete SAR antenna array will decrease. In this regard, such longer/larger subarray has to consume more power delivered from the T/R modules so as to form an active phased antenna array for the desired EIRP (equivalent isotropically radiated power) of the system. It would also bring another systematic problem in thermal dissipation. In this work, the length of the subarrays is selected to be $13.2\lambda_0$ (λ_0 is the corresponding wavelength at the center frequency) with 16 radiating elements working in C-band without extra power-distribution network, which is able to generate a required 2% relative bandwidth. In addition, as 4:1 frequency ratio is desired to obtain in this design for dual-band application, the spacing between the L-band subarrays is mainly determined according to the C-band array. Finally, in order to achieve a robust and light-weight structure, the four pairs of C-band 16-element dual-polarized subarray and a 4-element L-band subarray are integrated into one module, the aperture size of which is 734 mm × 154 mm.

A. C-band Dual-Polarized Antenna Subarray

As mentioned, the C-band dual-polarized antenna subarray is referenced from the authors' previous work about an X-band dual-polarized array reported in [14]. Apart from the working frequency changed, one more difference is the feeding structure that the complicated multilayer power-distribution feeding network is not necessary, therefore the H-Pol. and V-Pol.

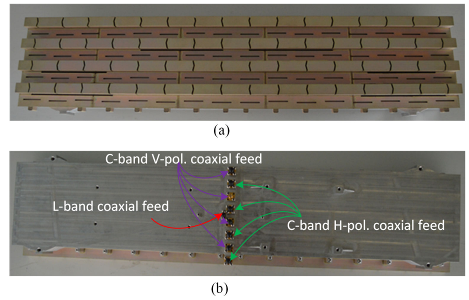

Fig. 2. Photograph of the fabricated dual-band dual-polarized antenna array. (a) Top view. (b) Bottom view.

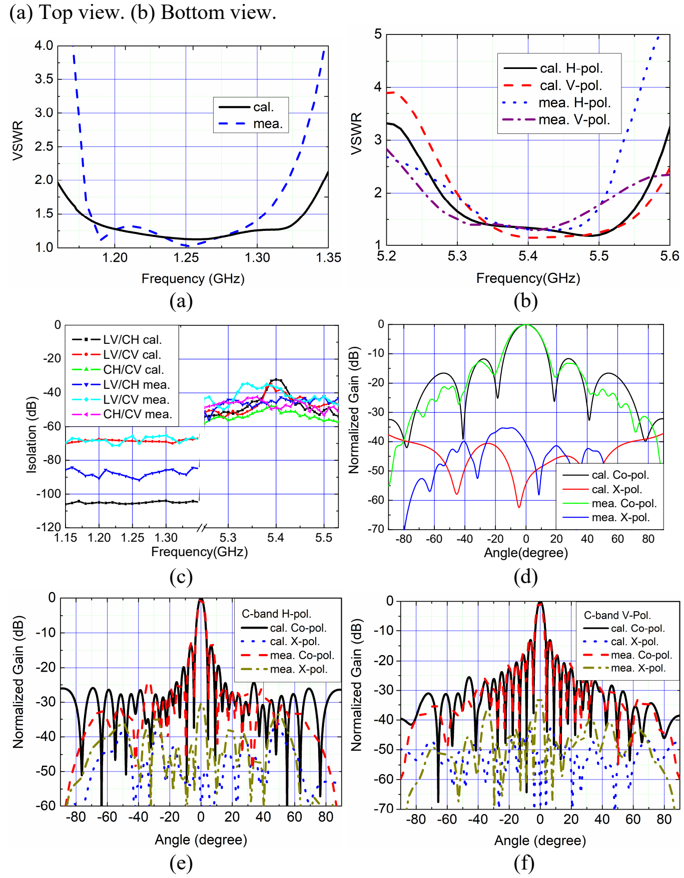

Fig. 3. Measured and simulated results. (a) VSWR of L-band subarray. (b) VSWR of C-band subarray. (c) Isolation. (d) Radiation patterns of V-pol. in L-band. (e) Radiation patterns of H-pol. in C-band. (f) Radiation patterns of V-pol. in C-band.

subarrays' waveguide channels only occupy a single layer, as shown in Fig. 1(a). During the design progress, the 16-element H-Pol. and V-Pol. subarrays are analyzed individually, and subsequently, four pairs of the dual-polarized subarrays are combined together and conducted an overall-optimization.

B. L-band V-Pol. Antenna Subarray

After the C-band dual-polarized antenna subarray is determined, a metal waveguide cavity is designed beneath the C-band array to form the L-band waveguide channel for power transmission. Except the two intrinsic ridges coming from the C-band V-Pol. waveguide channels (⑥ ⑦ in Fig. 1), two extra metal ridges are introduced at the bottom of the L-band waveguide channel to ensure the electromagnetic wave can be greatly transmitted in the L-band ridged waveguide. Meanwhile, the height of the ridges is adjusted to ensure that

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TABLE I Performance Comparison of The Proposed Antenna with Others

Parameters	[16]	[17]	Proposed
Freq./Pol.	35 GHz/HP 30 GHz/VP	1.25 GHz/HP&VP 9.6 GHz/VP	1.25 GHz/VP 5.4 GHz/HP&VP
Bandwidth	HP 688MHz VP 658MHz	8%@L-band 4%@X-band	11.36%@L-band 4%@C-band
Cross-pol.	-25dB@Ka band	-33 dB@X-band -27 dB@L-band	-30 dB@C-band -35 dB@L-band
Isolation	40 dB	40 dB@X-band 30 dB@L-band	34 dB@C-band 66 dB@L-band
Aperture Efficiency	36.3%HP 43.05%VP	95.9%@L-band HP 97.0%@L-band VP 66.9%@X-band	99.5%@L-band 99.1%@C-band, HP 99.4%@C-band, VP
Total Efficiency	--	-2.2 dB@ X-band -2.0 dB@ L-band	>85%@C-band >86%@L-band

the spacing of the adjacent radiating slots is equal to $0.5\lambda_g$, where λ_g is the waveguide wavelength at the center frequency. Note that the element offset of the L-band radiating slots is restricted because the "long" L-band resonant slots can only be designed on the limited spaces between the C-band H-Pol. and V-Pol. subarrays. Three longitudinal slots with different lengths set in a group, as shown in Fig. 1(b), are served as the basic radiating element of the L-band, instead of only one resonant slot opened in traditional slotted waveguide antennas. Such design is able to achieve a good impedance matching of the L-band subarray in a limited space. As a row of the C-band subarrays' feeding probes approximately divides the L-band waveguide channel into two independent cavities, as indicated in Fig. 1(d), it is difficult to excite the L-band subarray by single coaxial cable. Hence, in order to resolve this problem, a metal bridge is proposed to feed the two parts of the L-band waveguide simultaneously, the method of which can provide a better impedance matching inside the L-band feeding channel.

IV. SIMULATED AND EXPERIMENTAL RESULTS

The proposed DBDP antenna module has been designed and optimized to achieve desired performance in C- and L-bands simultaneously. The geometries of the proposed antenna module are depicted in Fig.1, in which, the width of all radiation slots is 2 mm and the thickness of the waveguide wall is 0.8 mm. For verification, the optimized antenna module has been manufactured in aluminum alloy, as shown in Fig. 2. Several fabrication processes are applied in the realization of the two antenna subarrays. The C-band dual-polarized antenna subarray is realized by the machine-milling and vacuum-welding process, while a metal cover is subsequently mounted on the back of the C-band array fixed by screws to form the waveguide cavity for the L-band antenna array. The operating bandwidth and radiation performance of the module are characterized experimentally. The comparison of the simulated and measured voltage standing wave ratio (VSWR) of a subarray is depicted in Fig. 3, from which a good agreement can be observed between the two sets of data. The measured results show the C-band V-Pol. subarray achieves 5.1% impedance bandwidth from 5.253 GHz to 5.528 GHz with VSWR<2.0, and that of the C-band H-Pol. subarray is 4% from 5.293 GHz to 5.510 GHz. Meanwhile, the impedance bandwidth of the L-band subarray is 11.36% from 1.179 GHz to 1.321 GHz. Compared with the numerical corresponding bandwidth results obtained from simulation of 5.24% (5.295~5.580 GHz), 5.35% (5.275~5.565 GHz) and 15% (1.159~1.347 GHz), respectively, the C-band measured bandwidths shift to lower frequency while the bandwidth of the L-band subarray is a bit narrower. Though the reason can be traced to the fabrication and assembly errors especially certain deformation may exist since such large-size antenna module is machined with a thin wall-thickness of 0.8 mm, the result deviation is still acceptable while particularly considering the high-integration level of the multifunctional antenna. The isolation between the C-band H-pol. and V-pol. subarrays is better than 42 dB. In addition, the isolation between the L-band V-pol. subarray and the C-band H-pol. (or V-pol.) subarray is 43 dB (or 34 dB) in C-band, and such isolation level reaches 84 dB (or 66 dB) in L-band, as shown in Fig. 3(c).

Two 1:4 microstrip power-dividers are used for the radiation characteristics measurement of the C-band antenna array. The radiation patterns of the DBDP antenna module are obtained from the planar near-field anechoic chamber. Results are also plotted in Fig. 3 at two typical frequencies of 1.25 GHz in L-band and 5.4 GHz in C-band, from which it can be seen that the patterns are comparable to the simulated ones. The radiations patterns of the C-band antenna show a good boresight beam (Co-pol.) of a uniformly-excited array, and the cross-polarization levels are lower than -30 dB. The measured radiation pattern of the L-band antenna also shows a good agreement with that of the calculated one. The directivities of a DBDP antenna array with a size of 1468 mm×1232mm are calculated based on the measured subarray radiation patterns. The directivities of the H- and V-pol. C-band (5.4 GHz) array are 38.63 dB and 38.64 dB respectively, and that of the L-band (1.25 GHz) array is 25.94 dB. Compared with the maximum directivity of an uniformly excited and equally spaced antenna array with the same size, the array achieves nearly a quite satisfactory aperture efficiency, as listed in Table I. Furthermore, the measured gains of the C-band H- and V-pol. antenna module are 25.9 dBi and 26.1 dBi (excluding the insertion loss of the 1:4 power-divider) with total efficiency of 85% and 88%, respectively. The measured gain of the L-band subarray is 9.95 dBi and its total efficiency is better than 86%.

V. CONCLUSION

A dual-band dual-polarized waveguide slot antenna module is investigated in this work with characteristic of shared-aperture and high-integration for SAR applications. The proposed antenna can fulfill the desired bandwidths in L-band and C-band with 4:1 frequency ratio. Both the C-band dual-polarized antenna and the L-band antenna are comprised of different linear-polarized subarrays interlaced with each other so as to achieve a miniaturized size. Good agreement between experimental and simulated results has been achieved, which verifies the design methodology of the proposed antenna module is feasible. This work can be a promising candidate for designing highly-integrated dual-band and dual-polarized antenna array in waveguide-based structures for advanced SAR applications.

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